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SYNCHRONIZATION OF REMOTE TIME SCALES VIA SATELLITE COMMUNICATION CHANNELS

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Advances in precision navigation, geodesy, geodynamics, and astrometry demands highly accurate locking of the time scales of remote time and frequency standards to National Standards [1, 2]. The existing methods that make it possible to compare time scales to within 1 μsec or less include transportable clocks, global satellite systems such as GLONASS and NAVSTAR, and LASSO system, and time scale comparison systems via meteoric communication channels.

The most accurate method of atomic time comparison is by observations with the aid of superlong-base radiointerferometers (SLBR). By processing a large enough number observations in a SLBR network, it is possible to get a comparison accuracy of 0.1 nsec or better [1]. Unfortunately, this method can be used to synchronize standards at network stations only and is not sufficient enough.

Duplex methods of time scale comparison via a satellite channel are most promising as far as nanosecond accuracy and high efficiency are concerned and scale comparison accuracies of the order of 1 nsec or less have been obtained in certain experiments [3-7].

The duplex method consists in two-way exchange of signals between two points where the clocks being compared are located via a satellite relay station. Such a two-way exchange makes it possible to large extent to eliminate all effects associated with signal propagation delay so that the comparison accuracy only depends on the signal shape, its processing method, and time interval measurement accuracy.

The duplex method is shown schematically in Fig. 1, where A and B are time scales at two stations, Δt is the relative delay between the two scales, t_A and t_B are transmitter delays at points A and B, r_A and r_B are the receiver delays at points A and B, S is the satellite delay, $a_\uparrow$ and $b_\uparrow$ are signal propagation delays from the stations of comparison to the artificial earth satellite (AES), and $a_\downarrow$ and $b_\downarrow$ are propagation delays from the AES to the comparison stations.

Clock comparison by the duplex method is carried out as follows. A signal generated at station A at the time T_{A1} by the A clock is transmitted at a frequency f_1 toward the AES. At the AES relay station the signal is received, coherently converted to frequency f_2 and transmitted toward the station B. The signal received at station B is processed and stops a time counter started at the time T_{B1} by the B clock. Signal transmission in the opposite direction is similar.

As a result of the signal exchange we get the times T_A and T_B corresponding to the time counter readings at both stations.

It is easy to see that difference between the time scales at stations A and B is given by

$$\Delta t=1/2[(T_A-T_B)+(t_A-t_B)+(r_B-r_A)+$$
$$+(a_\uparrow-a_\downarrow)+(b_\downarrow-b_\uparrow)]+T_r,$$

where T_r is the correction for relativity.

The quantities $(t_A - t_B)$ and $(r_B - r_A)$ can be found by transponder calibration at all comparison stations; as shown in [1], $(a_\uparrow - a_\downarrow)$ and $(b_\downarrow - b_\uparrow)$ are negligible and do not exceed 0.4 nsec. The relativistic correction can be calculated to within 0.1 nsec if the station coordinates and satellite motion parameters are roughly known [1]. Thus, by measuring T_A and T_B and calibrating the transponder one can find the time scale difference Δt to with-

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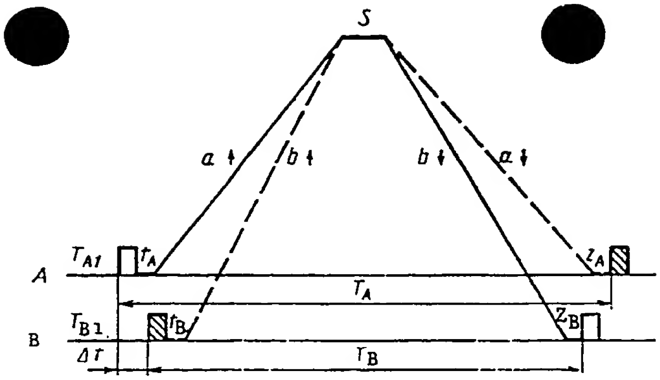

Fig. 1

in 1 nsec. It should be noted that to carry out the comparison in real time, the measured values must be transmitted to one of comparison stations through a special data transmission channel.

Reliable time scale comparison requires selection of an optimal signal for transmission of time marks. In the first works on the duplex method the signal was a single pulse or, sometimes, a television synchronization pulse. However, such signals do not ensure high synchronization accuracy in a real communication channel with limited bandwidth and noise. Consequently, a compound noise-like signal based on a maximum-length pseudorandom sequence was chosen to serve as a synchronization signal. Such a signal has good correlation properties and can be processed with high accuracy and reliability. The signal is noiseproof and simple to generate.

An experimental system, based on the equipment of the Kvazar-S department satellite communication network of the Academy of Sciences, was designed for duplex time scale comparison. At each comparison station the system contains a satellite communication transponder, a set of modems, time and frequency standards, a time interval meter, a time scale comparison circuit, and an automatic measurement system.

Most of the equipment, except for the comparison circuit and automatic measurement system, is conventional. The scale comparison circuit consists of receiving and transmitting sections. The transmitting section generates the noise-like signal whose phase is tightly locked to the local time scale. The transmitting section is timed by a 5-MHz signal provided by a time and frequency standard. The receiving section is a digital sequential correlator consisting of a synchronization signal generator the same as at the transmitting station, a circuit for comparing the received and local signals, and a circuit for synchronizing the local and received signals. The receiving section is timed by the clock pulse separated from the incoming signal in the demodulator.

The automatic measurement system is based on a DVK-3M computer and automatically records at each station the values of T_A and T_B together with the times at which the values were recorded.

Several experiments of time scale comparison using the existing communication channels were carried out in 1989-1990. The purpose of this experiment was to study the possibilities offered by this method and an analysis of errors occurring in the communication channel the delays introduced by its components. Two types of satellite communication stations were used in these experiments: a class I station with a 12-m antenna, a 1-kW transmitter, and a 300-K noise temperature receiver; and a class II station of the Kvazar-S system with a 4.3-m antenna, a 240-W transmitter, and 300-K noise temperature receiver. The set modems of the Kvazar-S system is intended for high-speed data transmission (10 Mbyte/sec) with frequency sharing and double phase-difference manipulation. A Gorizont geostationary relay station operating at 11/14 GHz was used in the experiments.

The experiments were conducted both in the "loop" mode (using a single satellite communication station) and with a 100-km base. The loop experiment made it possible to eliminate the effect of delays in transceivers and the relativistic effects and so to find the possibilities of the designed instrumentation. The values of T_A and T_B and directly the difference between them were measured in these experiments. In the 100-km base experiments

TABLE 1

Number of experiment	Data	SD ($T_A - T_B$), nsec	Averaging interval, min	Error, nsec
1	23.08.89	25,0	10	25.9
2	24.08.89	31,9	10	6.6
3	17.11.89	1.0	3	1.0
4	17.11.89	0.8	4	1.8
5	07.12.90	0,4	3	—
6	08.12.90	0,4	3	—

TABLE 2

Number of experiment	Duration of run, min	SD of the average at station 1, nsec	SD of the average at station 2, nsec	Resultant SD of average, nsec
1	14	0.6	0.8	1.0
2	2	1.3	1.4	1.9
3	3	0.9	1.2	1.5
4	4	1.3	1.3	1.8
5	4	0.9	1.1	1.4

T_A and T_B and the instants corresponding to them were measured at every station. Measurements were carried out in runs at different times of the day. The run duration varied from 2 to 14 min depending on the satellite velocity.

The results of measurements were first processed separately at each comparison station. The observation runs were processed by the method of least squares approximating some of them by a first-order curve and some, by a second-order curve depending on run duration and the satellite velocity during the observation. These curves were then compared to obtain the time scale differences.

The results of loop experiments are listed in Table 1. The difference of the deviation between standard scales measured by the duplex method and measured directly is listed in the last column.

Experiments 1 through 4 were carried out at a satellite communication station equipped with a test transponder, i.e., a device simulating the operation of a satellite transponder, which made it possible to find $(t_A - t_B) + (r_B - r_A)$. Experiments 5 and 6 were conducted at a station without a test transponder and the scale deviation was not measured. It should be noted that as indicated by the results of first and last experiments the random errors decrease as the instrumentation improves.

The difference between the time scales of standards and the rate of deviation of these scales were measured in experiments with a 100-km base. Calculations proved that with such a base the relativistic correction can be neglected. On December 13, 1991 and 12 h, 24 min and 30 sec, the scale difference was (9104810 + 2) nsec + X. X is equal to $(t_A - t_B) + (r_B - r_A)$ and represents the difference between delays in the receivers and transmitters of the satellite communication station and was not measured at this stage. The scale deviation rate was 0.01 nsec/sec. The results of this experiment are listed in Table 2.

The experiments show that the duplex method can be used to compare to within nanosecond accuracy remote time scales via a satellite communication channel using existing equipment. The random error calculated from the experimental data (of the order of 1 nsec) is quite satisfactory. However, to reduce the systematic error to the same level both the equipment and techniques must be further improved. The development of special modems for time scale comparison and of methods and instruments for measuring time delays in satellite communication transceivers is a fundamental topic for further investigations.

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